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International Compressor Engineering Conference

School of Mechanical Engineering

2002

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C20-5

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ABSTRACT

A computer program for thermodynamic performance of a scroll compressor was developed. The thermodynamic model assumes that the compression volumes of the scroll compressor are separated and interact only through leakages between them. The continuity and energy equations are used to calculate the pressure and temperature of the compression volumes. A leakage flow model is used to simulate the mass flow rate through all leakages. In this study, two different leakage models, isentropic and Fanno flow model, were studied to see its effects on the thermodynamic performance of the scroll compressor. The isentropic flow model shows a larger mass flow rate, compared with the Fanno flow model. CFD solutions obtained by using FLUENT show that the Fanno flow model is more accurate. The difference between the two leakages models grows larger as the clearance increases.

NOMENCLATURE

A: cross sectional area of a leakage passage
h: scroll height
p: pressure of compression chamber
T: temperature of compression chamber
y: lift of a check valve
ϕ: orbiting angle
ρ: density of compression chamber
ω: natural frequency of check valve
C_f: skin friction coefficient
m: mass of the compression chamber
R: gas constant
V: volume of compression chamber
α : involute start angle
ε: orbiting radius
θ_ε: involute maximum angle
ξ: damping coefficient of check valve

subscript

1 : inside scroll profile (involute)
ι: inflow
2 : outside scroll profile(involute)
o : outflow

INTRODUCTION

Scroll compressor is widely used in various industries due to its high efficiency and low noise characteristics, compared with conventional rotary and reciprocating compressors. So, a bunch of papers on its thermal, mechanical and dynamic analysis and design were already published in various conferences [1-3]. However, most thermal model of a scroll compressor use simple one-dimensional isentropic flow model to simulate the leakage flow in the scroll compressor. But, research on the leakage flow model is not sufficiently performed to validate the use of the isentropic flow model.

Present study aims to evaluate the accuracy of the isentropic flow model in a very practical way and suggest an alternative model that is more accurate. We developed a thermal analysis program to predict the performance of a scroll compressor and used this program to show effects of leakage flow model on the thermodynamic performance of a scroll. The accuracy of the leakage flow models is also checked using a commercial CFD code. We use FLUENT, a commercial CFD code, to compute the fluid flow through a leakage.

PREDICTION OF THERMODYNAMIC PERFORMANCE

Each compression volume of a scroll compressor was modeled as a separate system having its own mass as shown in Fig. 1. Its volume changes as the scroll orbits and can be expressed with respect to the orbiting angle. For example, the volume of the suction chamber (#1 in Fig. 1) can be expressed as

$$V = h\frac{a\varepsilon}{2}\{\phi(2\theta_e - \phi - \pi - \alpha_1 - \alpha_2) - 2(\theta_e - \pi - \alpha_1)\sin\phi - \frac{(\pi - \alpha_1 + \alpha_2)\sin(2\phi)}{2} + 2(1 - \cos\phi)\} \quad (1)$$

The mass, temperature and pressure of each volume is determined by solving the continuity, energy, and state equation summarized in the following:

$$\frac{dm}{dt} = \frac{dm_i}{dt} - \frac{dm_o}{dt} \quad (2)$$

$$\frac{dT}{dt} = T[\frac{1-\kappa}{V}\frac{dV}{dt} + \frac{1-\kappa}{m}\frac{dm_o}{dt} + \frac{\kappa T_i \frac{dm_i}{dt}}{mT} - \frac{\frac{dm_i}{dt}}{m}] \quad (3)$$

$$p = \rho RT \quad (4)$$

The scroll compressor used in this paper has a check at discharge port. We modeled it as a mass spring system. So, its motion can be determined by computing the following equation:

$$\frac{d^2y}{dt^2} = \frac{A_e(p_H - p_L)}{m_v} - 2\xi\omega\frac{dy}{dt} - \omega^2 y \quad (5)$$

Leakage flow models

The leakage flow through a clearance in the scroll compressor should be modeled to complete the thermodynamic model. There are two different kinds of clearance in the scroll as shown in Fig. 2. One is called radial clearance, and it causes the leakage flow in the circumferential direction. The other one is called tip clearance, and it leads to the leakage flow in the radial direction. In this paper, two leakage flow models are tried and evaluated by using the commercial CFD code FLUENT[4].

The isentropic flow model assumes that the leakage flow rate can be calculated by the following equation[5]:

$$\frac{dm}{dt} = C_d A p_u \sqrt{\frac{2\kappa}{(\kappa - 1)RT_u}}\sqrt{(\frac{p_d}{p_u})^{2/\kappa} - (\frac{p_d}{p_u})^{\frac{\kappa+1}{\kappa}}} \quad (6)$$

The second leakage flow model is a kind of Fanno flow[5]. It takes account of viscous effect in the leakage passage. We assume that the leakage passage has a constant area, and then the mass flow rate can be determined by solving the following equation:

$$4C_f\frac{\Delta x}{D_h} = 4C_f\frac{l^*}{D_h}f(M_1) - 4C_f\frac{l^*}{D_h}f(M_2) \quad (7)$$

where the function f(M) is defined as

$$4C_f\frac{l^*}{D_h}f(M) = \frac{1-M^2}{\kappa M^2} + \frac{\kappa+1}{2\kappa}ln(\frac{(\kappa+1)M^2}{2(1+\frac{\kappa - 1}{2}M^2)}) \quad (8)$$

CFD evaluation

We used FLUENT, a commercial CFD code, to evaluate the leakage flow models. Fig. 3 shows a model of a tip clearance. The inlet and outlet conditions, pressure and temperature, are results of the thermodynamic performance prediction. Computed mass flow rate is used to evaluate the mass flow rate predictions obtained by eqs. (5) and (6).

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RESULTS AND DISCUSSION

A scroll compressor of 150(cc) manufactured by Mitsubishi was simulated in this paper. Detailed data of the compressor is summarized in Table. 1. The thermodynamic performance of the scroll compressor was obtained by solving eqs. (2)-(5). We used the 4^{th} order Runge-Kutta method to integrate all governing equations in time. One revolution of the scroll compressor was divided into 3600 time steps. The leakage flow through all clearances was modelled in two different ways, i.e. assuming either of isentropic and Fanno flow.

Fig. 4 shows variation of pressure in 6 compression chambers, from #2 to #7, with orbiting angle. The pressure rise in the figure indicates that the compression ends at about $800(^{o})$. Afterward, pressure oscillates due to action of the check valve at discharge port. The difference in the leakage flow rate between two leakage flow models appears as difference in the pressure distribution. Fig. 5 shows variation of mass in 6 compression chambers with orbiting angle. Figure shows that the leakage flow led to larger mass in the compression chambers, especially in the chambers 4 and 5. Larger mass is caused by larger leakage flow rate and also means decrease of thermal efficiency. The difference in the mass between the two leakage-flow models goes up to 5%. Fig. 6 shows variation of temperature in 6 chambers with orbiting angle. As expected, the temperature in the compression chambers predicted by the isentropic flow model is much higher than that by the Fanno flow model. The isentropic flow model predicts discharge temperature as about $13(^{o})$ higher than that without tip clearance leakage flow. This is believed too much over predicted, even compared with the Fanno flow solution.

Fig. 7 compares the leakage flow rate through the tip clearance between the chambers 5 and 6. The isentropic flow model shows much over predicted flow rate, while the Fanno flow model shows a reasonable flow rates. Fig. 8 shows a similar behaviour for the leakage flow through the tip clearance between the chambers 4 and 7. In all comparisons made in this study, the isentropic flow over predicts the leakage flow rate compared with CFD solutions. The Fanno flow model showed a quite satisfactory agreement with the CFD solution.

Fig. 9 shows velocity profiles along the tip clearance between the chambers 4 and 7. As the clearance is quite small, the velocity profiles show laminar flow behaviour. The pressure gradient is so nonlinear that the flow is developing over the whole region.

Fig. 10 shows variation of overall performance of the scroll compressor with the tip clearance. Since the isentropic flow model predicts excessive leakage flow rate, its adiabatic efficiency is much lower than that by the Fanno flow model. Anyway, the slope of the adiabatic efficiency decreases as the tip clearance increases. But, the slope of the isentropic flow model is much larger than that of the Fanno flow model. So, its accuracy of the thermal prediction becomes worse. The discharge temperature increases with the tip clearance as expected. But, the rate of the temperature increase by the isentropic flow model is larger than that by the Fanno flow model.

CONCLUSIONS

Effects of leakage flow model on the thermodynamic performance of a scroll were studied in detail. The two leakage flow models, the isentropic and Fanno flow model, were implanted into an analysis code to see their effects on the thermodynamic performance of a scroll compressor. They were also validated against CFD solutions. The Fanno flow model shows a better agreement with CFD solution in all comparisons. The isentropic flow model over predicted the leakage flow. It eventually led to lower thermal efficiency and higher discharge temperature. The difference between the isentropic and Fanno flow model becomes larger as the clearance increases.

ACKNOWLEDGEMENTS

This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the Regional Research Center for Advanced Climate Control Technology at Sun Moon University.

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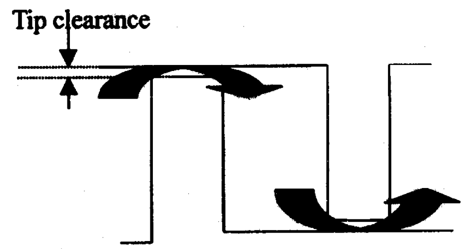
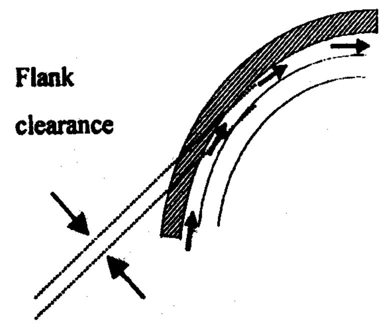
	Parameter	Value	Parameter	Value
Scroll design parameter	Displacement	150 cc/rev	Scroll height	44.5 mm
	Scroll thickness	4.0 mm	Basic circle radius	3.4 mm
	Involute maximum Angle	945?	Orbiting radius	6.5 mm
	$\alpha_1 = 0$, $\alpha_2 = 68.4$, $\theta_A = 354.4$, $\theta_c = 354.4$ $\gamma = 112.4$, $\beta = 14$, $r_1 = 3.9$ mm, $r_2 = 10.4$ mm			
Scroll compressor design parameter	Suction plenum	340 cc	Discharge plenum	150 cc
	Suction port area	1.8 cm2	Discharge port area	0.8 cm2
	Discharge port periphery	41 mm	Discharge port volume	2.6 cc
Discharge valve	Natural frequency	218.7 Hz	Damping coefficient	0.02
	Stop height	3.1 mm	Mass	0.5 g
	Thickness	0.4 mm		
Operating conditions	Refrigerant	R-134a	Suction pressure	294.3 KPa
	Discharge pressure	1471.3 KPa	Superheat	10
	Compressor speed	2000 rpm	Suction temperature	11
	Radial clearance	15 μm	Axial clearance	10 μm

Table.1 Scroll compressor specification



(a) tip clearance



(b) radial clearance

Fig. 2 Leakage flows

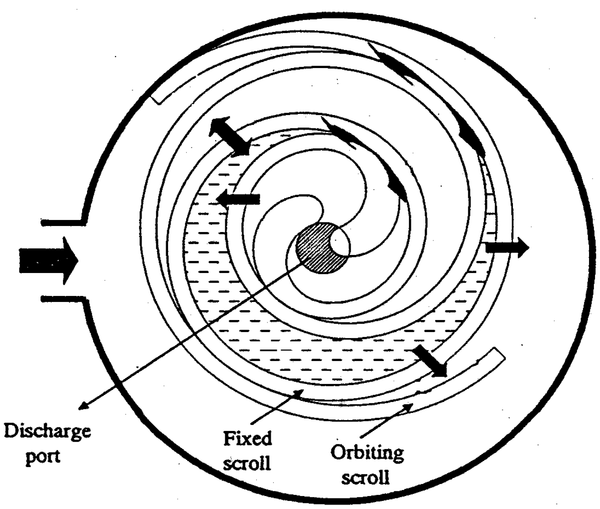


Fig. 1 Thermodynamic model of a scroll compressor

Fig. 3 Tip clearance flow model

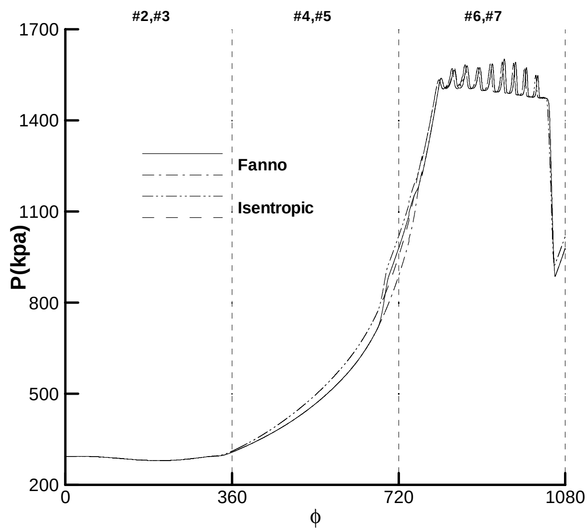


Fig. 4 Variation of pressure in 6 chambers

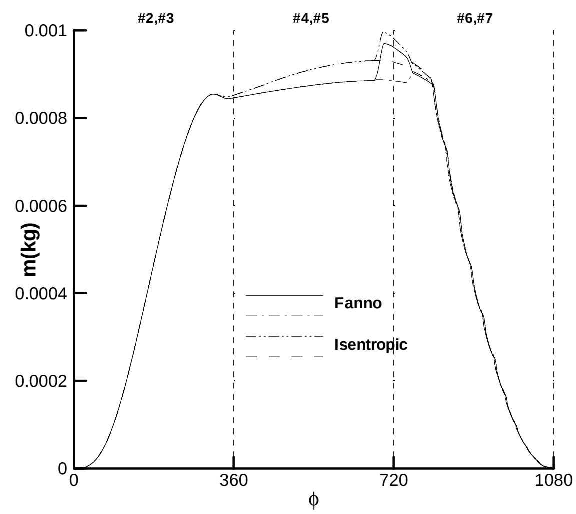


Fig. 5 Variation of mass in 6 chambers

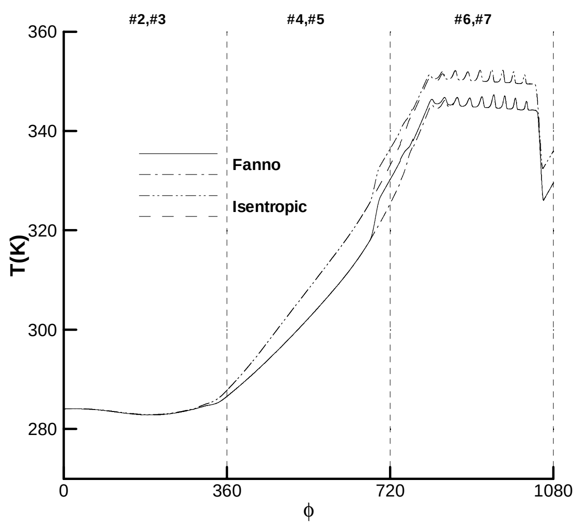


Fig. 6 Variation of temperature in 6 chambers

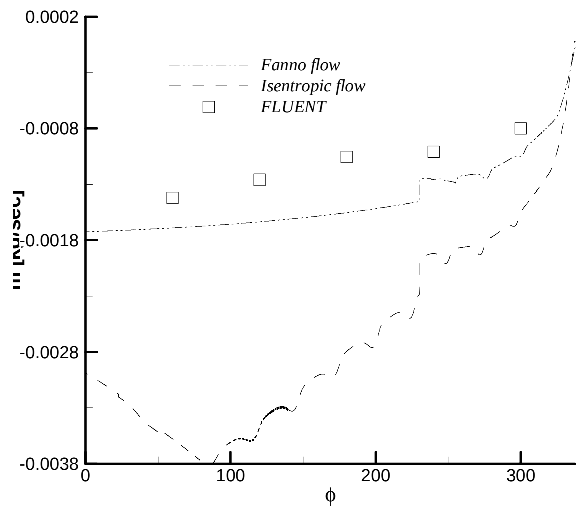


Fig. 7 Leakage flow rate between chambers 5 and 6

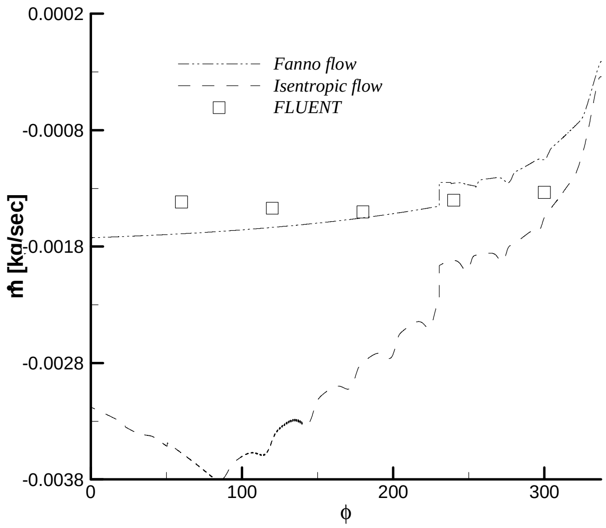


Fig. 8 Leakage flow rate between chambers 4 and 7

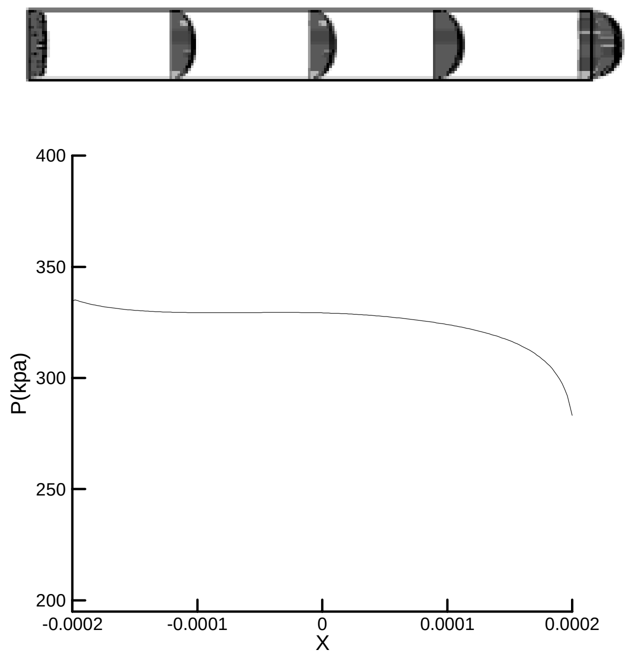


Fig. 9 CFD solution for the leakage flow

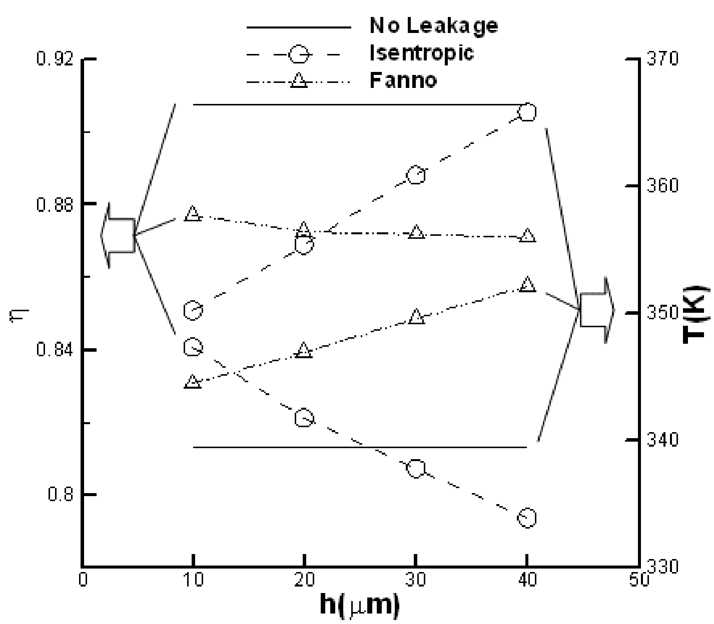


Fig. 10 Effect of the tip clearance on overall Performance